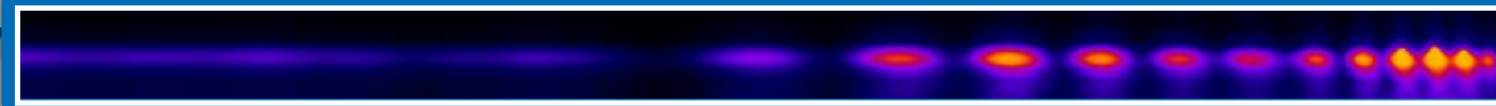
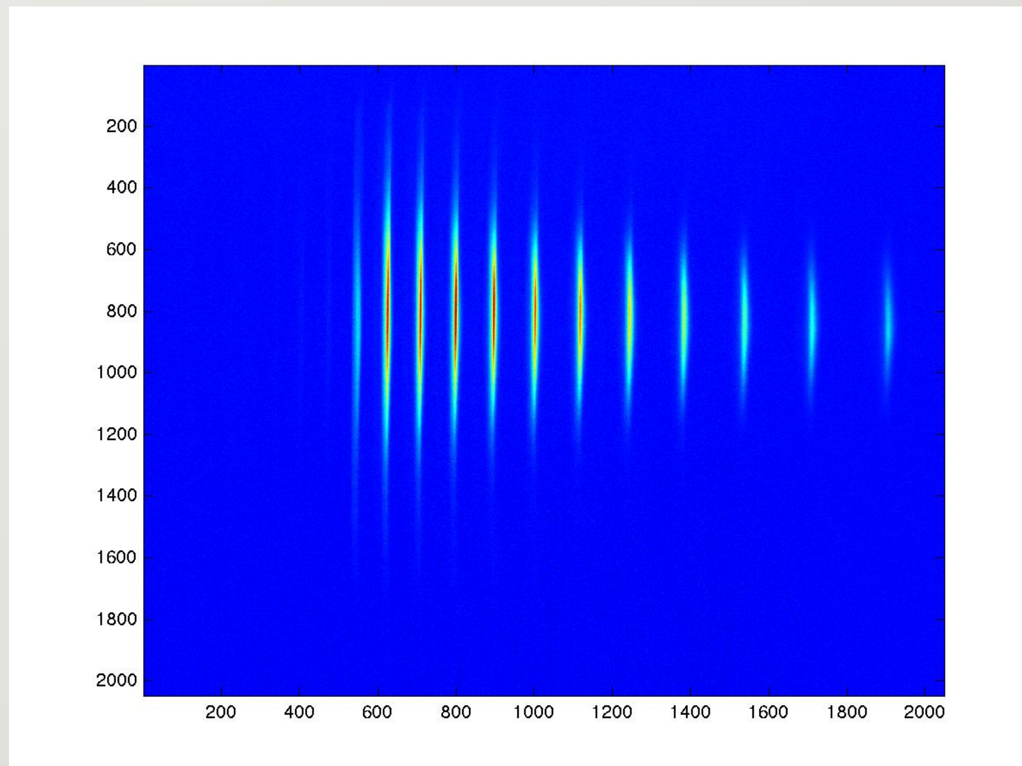


Coherent extreme ultra violet light sources using highly efficient High Harmonic Generation



M. Wünsche[1,2], A. Hage[3,4], M. Taylor[4], M. Yeung[2,4], ,C. Rödel[1,2], B. Landgraf[1,2], A. Willner[3], M.J. Prandolini[2], M. Schulz[3], T. Gangolf[1], S. Fuchs[1,2], H. Höppner[3], R. Riedel[2] B. Dromey[4], F. Tavella[2], C. Spielmann[1], M. Zepf[1,2,4], G. G. Paulus[1,2]

[1] Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Germany
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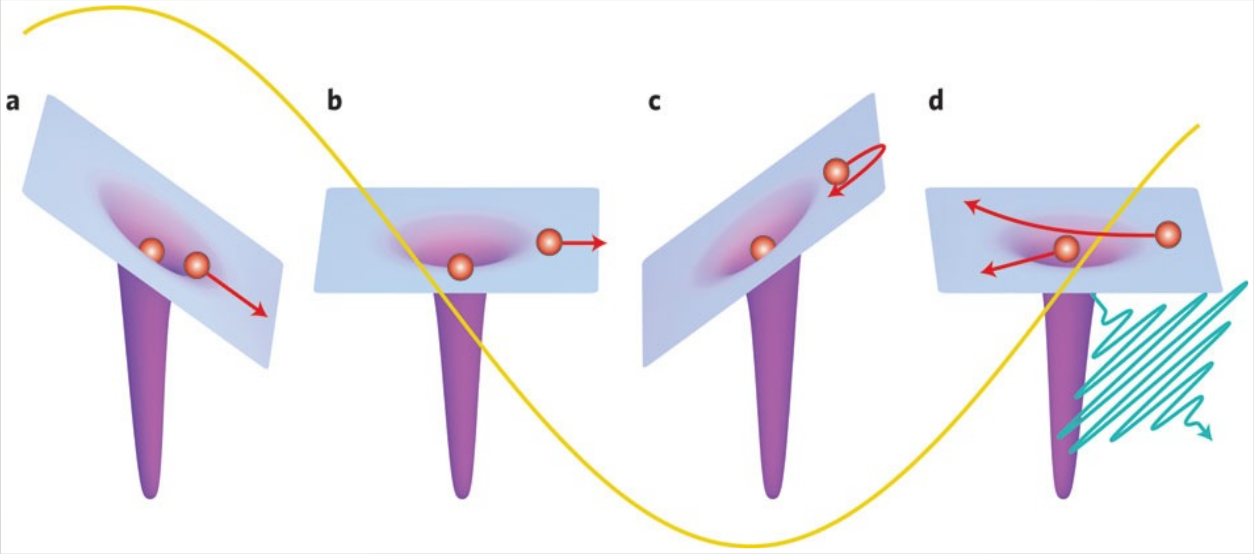
[3] Deutsches Elektronen Synchrotron, Germany
[4] Queen's University Belfast, United Kingdom

Alternative EUV sources

- Synchrotron/FEL: large scale facility is needed
- Plasma sources: limited by atomic line emission
- Plasma sources: high divergence (4*Pi)
- monochromatic sources

- Could HHG be an alternative source?



Midorikawa, Nature Photonics 5, 640–641 (2011)

Outline

1. Mechanism of High Harmonic Generation – HHG
2. Using different concepts of HHG
3. Field of application – XUV Coherence tomography

Properties of HHG

- Pulse duration in attosecond regime
- Laser-like radiation
- driven by small scale lab-based fs-lasers
- intrinsically broadband
- efficiency up to 10^{-5}

Mechanism of High Harmonic Generation

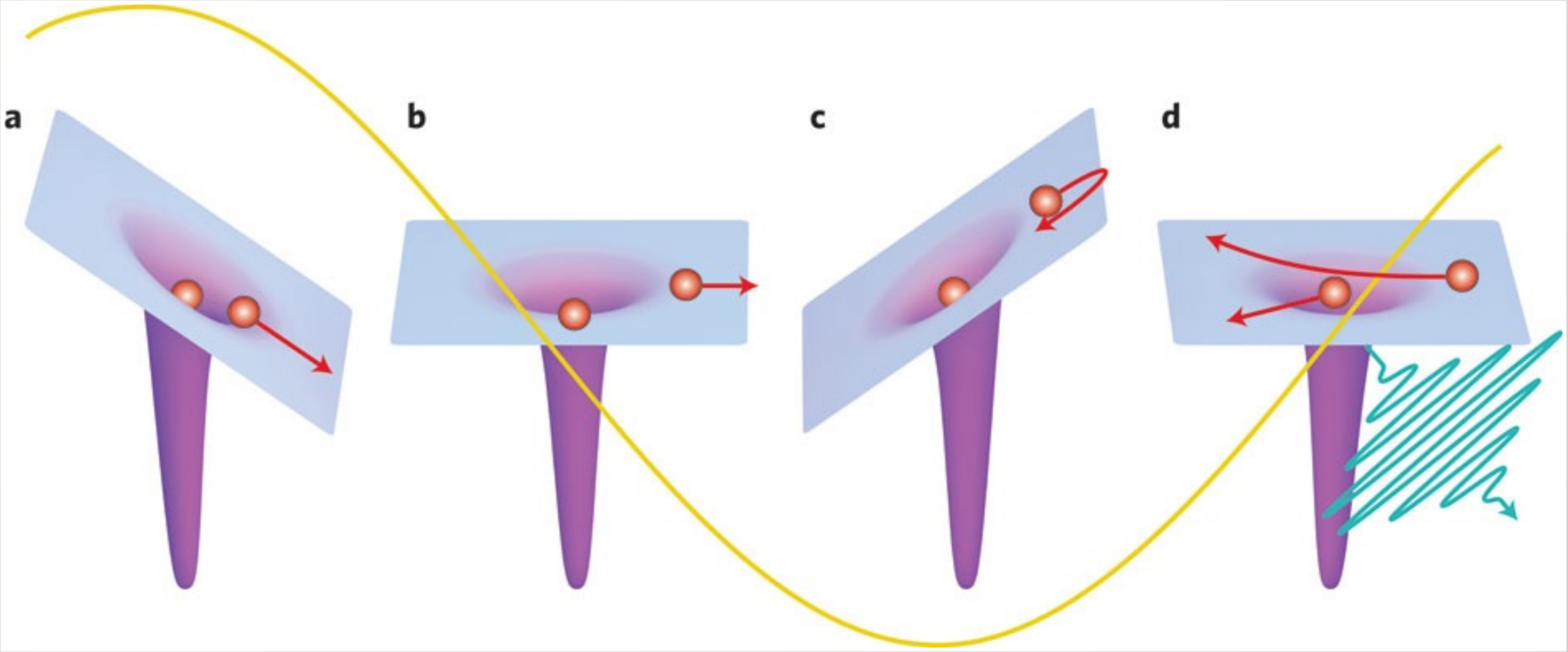
- Iluminate an atom with an intense laser field – what happens?
  - not a simple field ionization: $E_{\text{photon}} > U_{\text{atom}}$
  - for NIR-laser and gases: $E_{\text{photon}} << U_{\text{atom}}$
- High non-linearity: $N \cdot E_{\text{photon}} = U_{\text{atom}}$

Example	photon energy	Number of photons
Hydrogen (U=13.6 eV)	800 nm (1.55 eV)	>8
Helium (U=24.58 eV)	800 nm (1.55 eV)	>15

Non-pertubative: Three-step model

Corkum, PRL 71 13, 1994-1997 (1993)

- a. Ionization
- b./c. Propagation in the laser field
- d. Interaction with parent ion

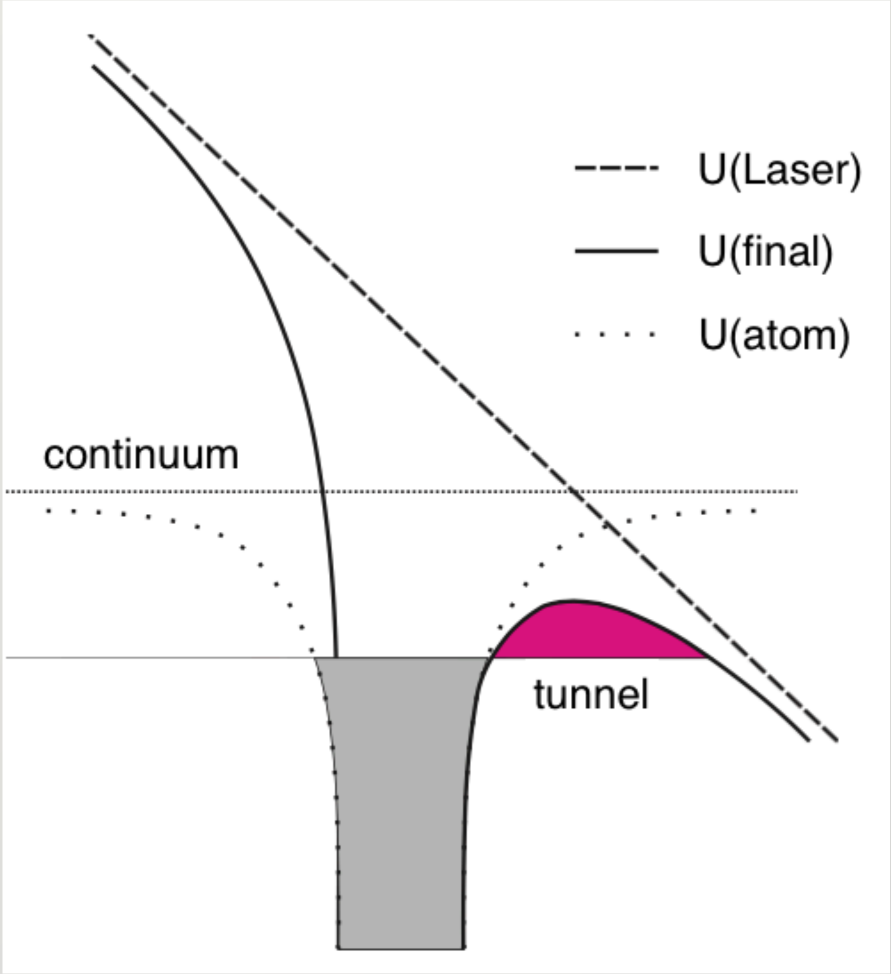


Midorikawa, Nature Photonics 5, 640–641 (2011)

Ionization

- Potential deformation in linear fields

$$U_{\text{final}}(\vec{r},t) = U_{\text{atom}} + U_{\text{laser}} = -\frac{1}{4\pi\epsilon_0}\frac{Ze^2}{|\vec{r}|} - e\vec{E}(\vec{r},t)\vec{r}$$

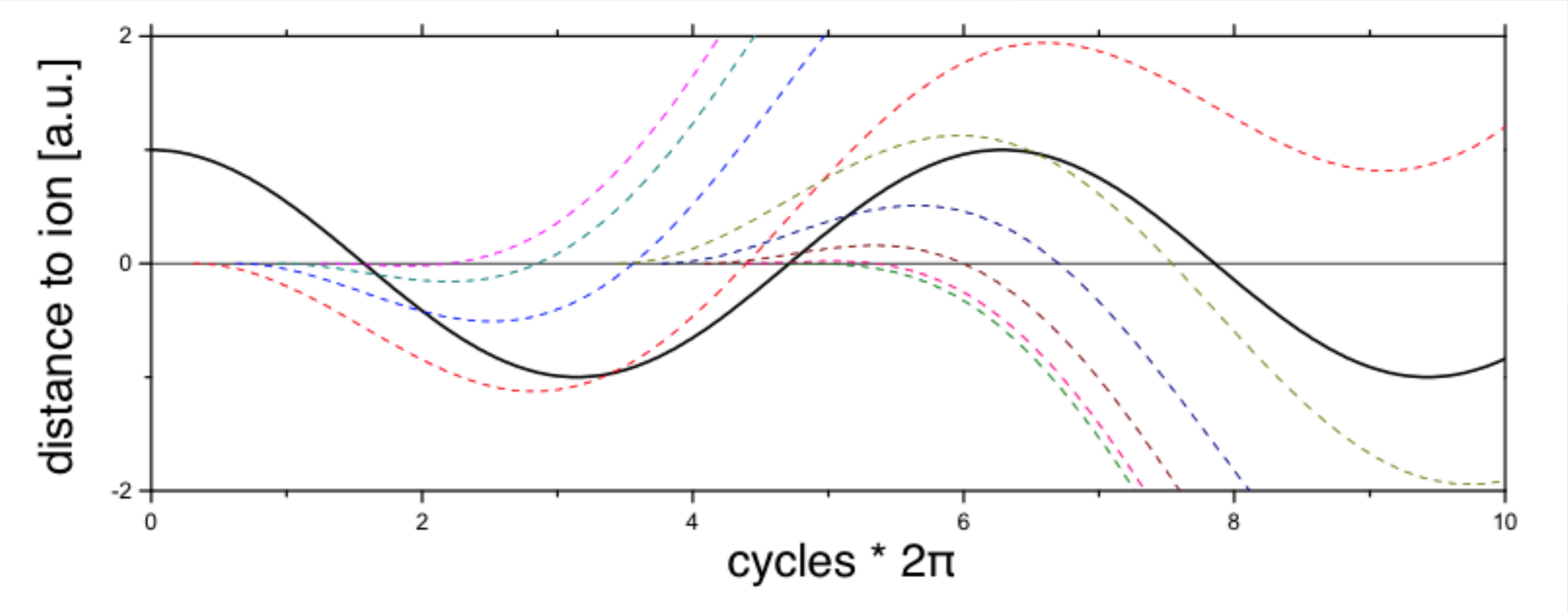


- Tunneling through the atomic potential

Propagation in the laser field

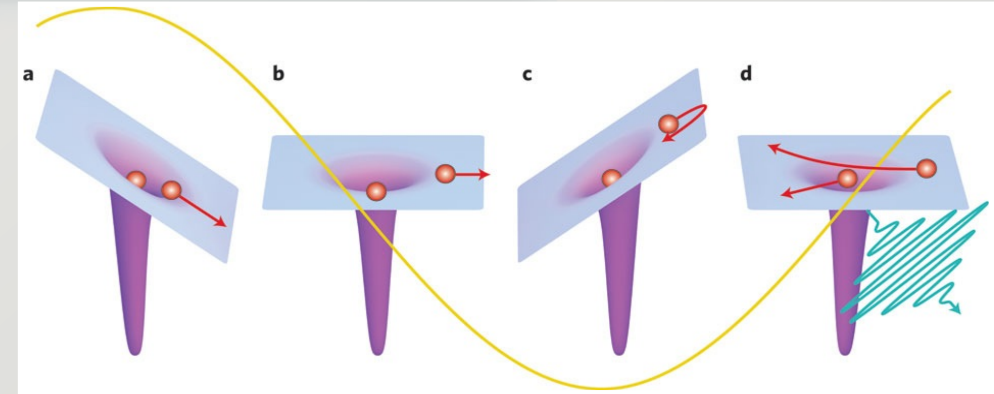
- Electron follows the field
- Canonical momentum with vector potential $\vec{A}$

$$\vec{p}(t_0) + e\vec{A}(t_0) = \vec{p}(t_1) + e\vec{A}(t_1)$$



- Can return to the parent ion

Recombination



- Return energy

$$E_{\mathrm{return}} = \frac{e^2}{2m}(A(t_1) - A(t_0))^2 \leq 3.17 U_{\mathrm{P}}$$

- ponderomotive potential =kinetic energy of the laser field

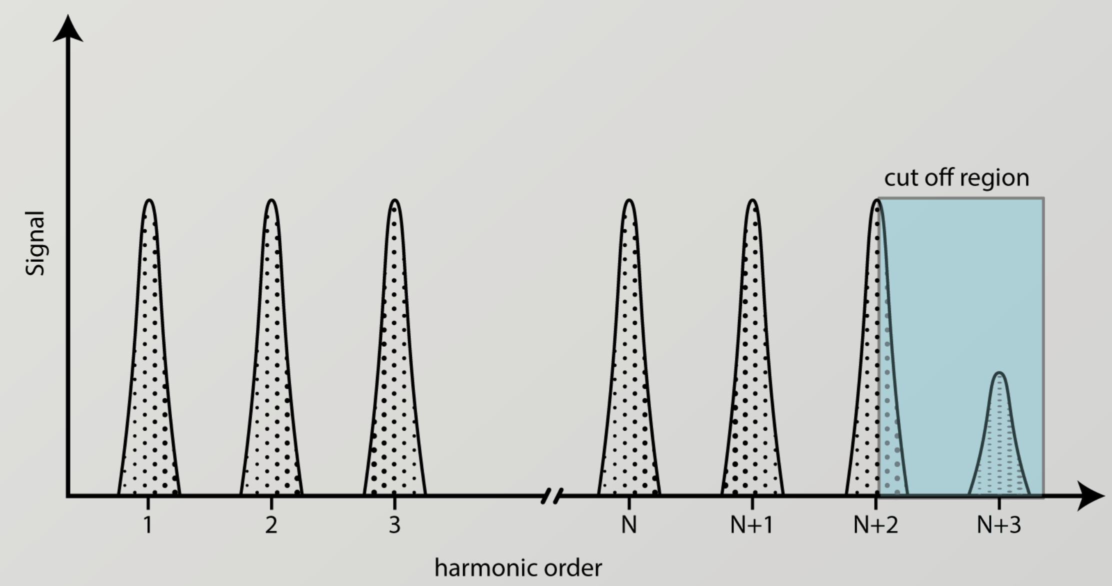
- Cut-off energy: $\hbar\omega_{\mathrm{CO}} = I_P + 3.17 U_P$

$$U_P \approx 10^{-13} I \lambda^2$$

photon energy	intensity	Pondermotive Potential	Cut-off
800 nm (1.55 eV)	10^{14} W/cm^2	U_P=6.4 eV	E=36 eV (@Ar) , λ=34nm
1800 nm (0.69 eV)	10^{14} W/cm^2	U_P=32.4 eV	E=118 eV (@Ar), λ=10.6nm

beam characteristics

- periodic process every laser half-cycle
- Frequency comb $$E_{\mathrm{harm}} = N \cdot E_0$$
- efficiency up to 10^{-5}
- Divergence: ~mrad
- Output power:



Laser pulse	intensity	Average Power in XUV
10W (our laser)	10^{-5}	100µW
2kW (fiber laser)	10^{-5}	20mW

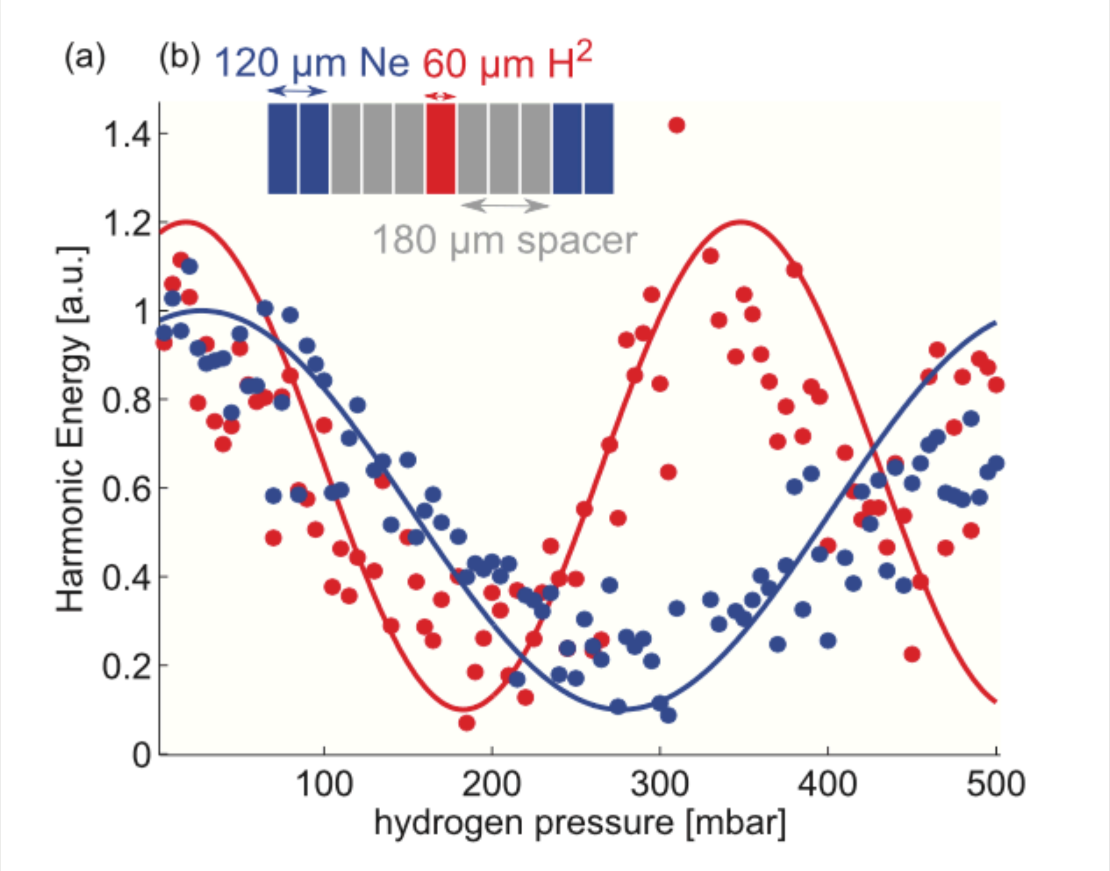
Quasi-Phase matching

- Producing XUV depends on phase

$$\Delta\varphi = \varphi_{\mathrm{fund}} - \varphi_{\mathrm{XUV}} < \pi$$

- Dephasing limit for HHG $\propto l \cdot p$

- Reabsorbing XUV

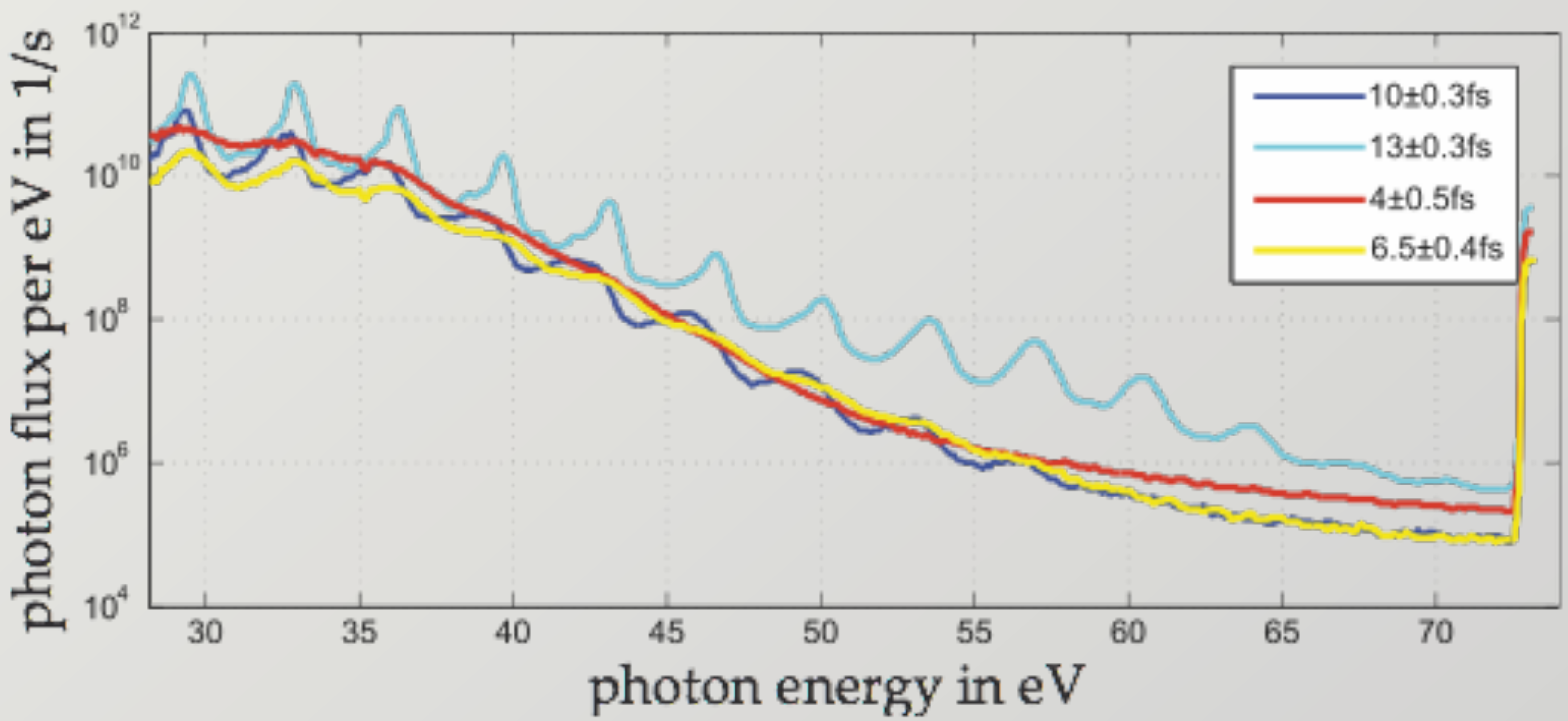


A. Hage,..., M. Wünsche, RSI 103105 (2014)

- Overcome: stop reabsorbing by using a phase shifter

2. Spectral broadening

- Using few-cycle laser pulse (cycles <3)
- Reduced number of temporal emitters
- Flattening spectral distribution



spectrum	photon yield
25…55eV	$10^7 \ldots 10^{10}$ $eV^{-1}\,s^{-1}$

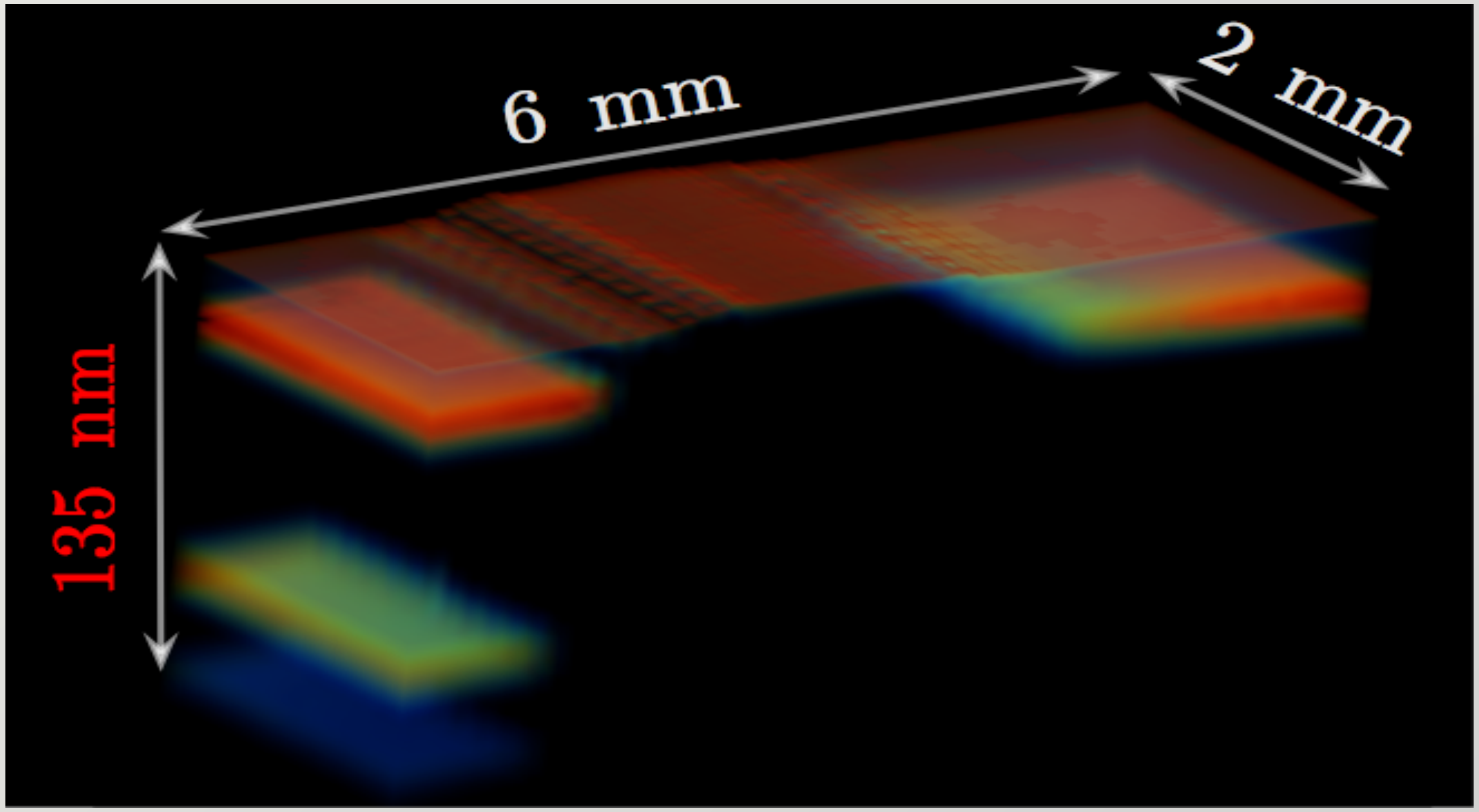
Conclusion

- HHG: laser-like, coherence, spectral broadness, small divergence
- Not usable for Lithography
- Useful as imaging source

Field of Application: XUV Coherence tomography

- Using broad spectrum of XUV for resolution
- Resolution: few nm

S. Fuchs,,..., M. Wünsche, Appl. Phys. B (2012) 106:789-795



- Visit the poster: Nanometer optical coherence tomography using broadband extreme ultra violet light (S44)

Thank you for

your attention!